MICROEMBOLI INTRODUCTION WITH VENOUS CANNULA OBSTRUCTION AND VARYING METHODS OF VENOUS DRAINAGE

THESIS

By

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ABSTRACT

During extracorporeal circulation, negative pressure is generated in the venous cannula and line. Whenever there is negative pressure, the potential exists that gaseous microemboli (GME) will be introduced into the blood, whether it is pulled out of solution or into the cannula through the purse string sutures. This negative pressure is augmented when the vena cava collapses over the tip of the cannula, increasingly the likelihood that GME enter the cannula and venous line. This research aimed to determine if one particular method of venous drainage (siphon, vacuum, or kinetic) causes more GME to be introduced across the venous cannula when the vena cava collapses over the cannula (referred to as “chugging”) than the other methods of drainage. A circuit was constructed that is capable of utilizing all three methods of venous drainage, and used a Penrose drain to simulate the vena cava. GME readings were taken pre and post cannula using the EDAC Quantifier blood circuit monitor. Readings were taken at venous line pressures from zero to -80 mmHg. Chugging began at -40 mmHg. Results showed that upon the onset of chugging there was a transient increase in GME introduction during all three methods of drainage. Vacuum-assisted drainage introduced a statistically significant greater number or GME across the cannula than kinetic or siphon drainage at all negative pressures.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

In all cases involving extracorporeal circulation, negative pressure is generated in the venous line while blood is being siphoned from the patient. This negative pressure has the potential to extract dissolved gases from the blood, or pull atmospheric air into the circuit, creating gaseous microemboli. Microemboli are potentially fatal if they are to enter the patient’s circulatory system. Consequently, minimizing the introduction of microemboli is one of the perfusionist’s highest priorities. The pressure in the venous line and venous cannula becomes very negative during periods of time where the patient's vena cava obstructs the opening of the cannula, potentially increasing the likelihood that microemboli will form. This research aims to determine if the method of venous drainage can reduce the number of microemboli introduced across the venous cannula when the vena cava collapses over the tip of the cannula.

This problem is of importance at the international level. While the chances of a patient becoming severely debilitated or dying during the perioperative period of their open heart procedure are relatively low (about 2 out of every 100 bypass patients will suffer a stroke directly related to their surgery), the need to take steps that further ensure patient safety is significant (1). This is especially true when one considers that 2,000 open-heart bypass procedures are preformed every 24 hours worldwide (12).

1.2 BACKGROUND

Just 40 years ago, the chances of a person surviving with a congenital heart defect or in congestive heart failure were grim. The complexities of doing surgery on a beating heart while still maintaining adequate perfusion to the rest of the patient’s body made such a procedure one few surgeons were confident in attempting. When such heart procedures were tried, survival rates where extremely low. However, this has all changed with the evolution of the extracorporeal blood circuit. The extracorporeal circuits used in open heart procedures today allow the blood to totally bypass the heart and lungs, yet still undergo the necessary gas exchange and be pumped through the rest of the body. Furthermore, the heart can be completely arrested since it is not needed to perfuse the patient's organs and tissues. Thus, the surgeon can work in a motionless surgical field, while the vitality of the patient is preserved. Keeping the heart arrested during surgery has revolutionized the capabilities of the surgeon and introduced a new arsenal of techniques that can be utilized to treat an ailing heart while simultaneously reducing intraoperative morbidity and mortality.

The extracorporeal circuits used in the operating room vary from case to case, but they all function to accomplish the same common goals. These goals are to maintain adequate perfusion, oxygenate the blood, remove carbon dioxide from the blood, and to control the temperature of the blood. Regardless of the exact circuit design, all accomplish these goals in a similar fashion. Blood is removed from the patient via a small tube called a cannula. The cannula is typically placed into a patient's right atrium or vena cava, and the blood is drawn out and runs down a long segment of polyvinylchloride tubing (the venous line) into a venous reservoir. From the reservoir, the blood goes through a pump and into an oxygenator. The pump in the circuit replaces the normal function of the patient's heart, and the oxygenator replaces the normal function of the patient's lungs. In the oxygenator, the blood receives oxygen and gets rid of carbon dioxide it collected in the body. The blood then goes through a heat exchanger, where it is often cooled. Cooling the blood will cool the patient. The colder a patient is the slower his or her metabolism, and thus the lower his or her oxygen demand. For this reason, hypothermia is a tool often used during bypass to enhance patient safety. Finally, the now oxygenated (arterial) blood is sent through filters and another cannula (often in the aortic arch) and back into the patient.

While the advancements in safety and effectiveness regarding extracorporeal circuits and cardiac bypass surgery have been vast over the past 40 years, danger still perpetually looms throughout the course of a procedure. Further research must be done to minimize this danger. Cardiac bypass surgery can never be considered completely safe and there is a plethora of room for further advancements.

1.3 REVIEW OF LITERATURE

Research shows patient brain damage during cardiac bypass surgery is all too common. Likosky et al. (1) reported that some degree of cognitive dysfunction directly related to the procedure is found in up to

80% of postoperative patients. 1% to 3% of patients experience strokes. A variety of factors contribute to patient morbidity and mortality during cardiopulmonary bypass, but research suggests that cerebral microemboli introduced while the patient is on bypass is the primary factor leading to neurocognitive impairment (2). Microemboli can exist as solid particles derived from lipids, thrombi, and atherosclerotic plaques, but the majority exist as small gaseous microbubbles (3).

One major cause of gaseous microemboli (GME) entrapment in the extracorporeal circuit is the negative pressure developed across the venous cannula as blood is siphoned from the patient to the venous reservoir (4). This negative pressure can drawl atmospheric air into the venous line through loose purse string sutures around the venous cannula, or can extract dissolved air from the blood, forming GME (1).

Research has shown that the type of venous drainage utilized during bypass has a direct effect on how many GME are introduced to the patient (5). Three main types of venous drainage are currently used in the operating room: siphon drainage, kinetic assisted venous drainage (KAVD), and vacuum assisted venous drainage (VAVD). Siphon drainage is passive and uses the pressure differential created by the height difference between the patient and the venous reservoir to drive the blood flow. KAVD uses a pump (centrifugal or rollerhead) to drawl the blood from the patient. VAVD uses a vacuum attached to the venous reservoir to suck the blood from the patient. KAVD and VAVD are often utilized because the negative pressure they create improves venous drainage (6). In fact, Humphries et al. (7) found that for each 40mmg increase in vacuum during VAVD, blood flow was increased by 42.08%. However, the increased negative pressure that improves flow also increases the number of GME that become entrapped in the extracorporeal circuit and can potentially be pumped into the patient. Rider et al. (5) reported that after a stop cock on the venous line was left open for 30 seconds during VAVD, it produced 41 GME distal to the arterial line filter. Only 5 GME were identified distal to the arterial line filter during siphon drainage. This data was collected under normal flow conditions.

One aspect of venous drainage that has not been studied is how these same methods of drainage impact the formation of GME when the vena cava collapses over the tip of the venous cannula. The vena cava are the main routes back to the heart for blood, are relatively thin walled, and are the veins most often cannulated during cardiopulmonary bypass. If the suction from the venous line surpasses the venous return, the negative pressure will cause the walls of the vena cava to collapse over the tip of the cannula. When this “chattering” occurs, flow and pressure in the venous line become very turbulent. This phenomenon is commonplace in the OR, and is often initiated momentarily during surgery and research to give the perfusionist an idea of what the maximum flow through the circuit can be (8).

1.4 OBJECTIVES

The overall objective of this study is to determine if a particular method of venous drainage has a tendency to introduce a greater number of GME across the venous cannula during periods of vena caval collapse over the venous cannula than the other drainage methods. Which method will introduce the least number of GME? Will the type of venous drainage even have an effect on the number of GME introduced, or will the turbulent flow and fluctuations of pressure in the cannula do to the collapse of the vena cava over the tip have no effect on the number of GME introduced?

A number of research articles suggest that kinetic assisted venous drainage is the method responsible for the introduction of the greatest number of GME into the cardiopulmonary bypass circuit under conditions of normal flow (5,9). These papers concluded that kinetic assisted drainage techniques can cause excessive negative pressure in the venous line (< -35 mmHg). This negative pressure can entrain air into the line, or cause the spontaneous formation of GME (10). While these research articles did not directly address GME introduction during vena cava collapse, it is hypothesized that this same trend will be seen in this research. KAVD will be responsible for the largest number of GME introduced into the extracorporeal circuit during periods of venous drainage when the vena cava collapses over the cannula.

CHAPTER 2

METHODOLOGY

2.1 PROCEDURES

This problem was investigated by testing the three methods of venous drainage, and measuring how many GME they introduced across the venous cannula. When testing siphon, the height gradient between the venous cannula and the venous reservoir was set so that the pressure in the venous line is 0 mmHg. The GME count after one minute was recorded, and then the height gradient was increased so that the pressure in the venous line became -20 mmHg. The GME count was taken after another minute, and then the pressure in the line was decreased to -40 mmHg, and finally -60 mmHg, with a GME count being taken after one minute at each negative pressure. Vacuum and kinetic drainage data were collected in a similar fashion, except that to decrease the venous line pressure during VAVD, the vacuum was increased, and to decrease the line pressure during KAVD, the RPMs on the pump were increased. Three trials were done for each method of venous drainage.

The blood was kept at a constant temperature of 32˚C, and flow was kept at 2.5 L/min. This flow helped maintain a relatively low CVP (0-5 mmHg). The hematocrit of the bovine blood was 21%.

2.2 DESIGN

A circuit was constructed (Figure 1) that was capable of utilizing all three methods of venous drainage. An 18” (1 inch I.D.) Penrose drain was used to simulate the vena cava. Penrose drains are often used in experiments as models for vena cava because their compliance is similar to that of the vein’s (14).

GME readings occurred at two locations in the circuit: (1) at the exit of the bag reservoir acting as the patient, (2) on the venous line right after the cannula. The readings at the exit of the bag reservoir reported how many air emboli were entering the venous cannula, and the readings on the venous line just after the venous cannula reported how many emboli left the cannula. The difference between these values is the number of air emboli introduced across the cannula.

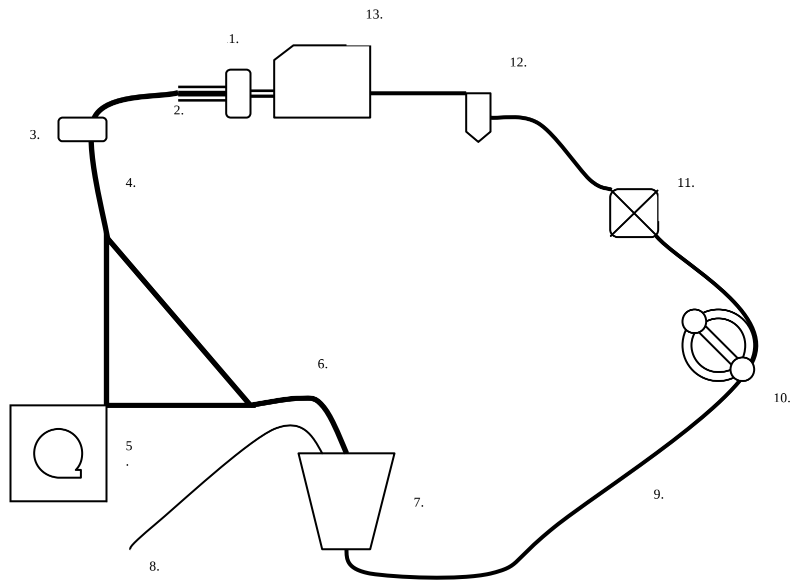


Figure 1: Circuit Design

1. EDAC (pre-cannula)
2. 18” Penrose drain (1” I.D.) with Baxter Dual Stage 36/51 Fr. cannula (model for cannulated vena cava)
3. EDAC (post-cannula)
4. Site used to monitor venous line pressure
5. Biomedicus centrifugal pump
6. ½” tubing
7. COBE CV Smart VVR 4000i venous reservoir
8. Vacuum
9. 3/8” tubing
10. COBE roller head arterial pump
11. Apex oxygenator/heat exchanger
12. Affinity 38µ arterial line filter
13. Collapsible reservoir (model for patient)

2.3 DATA AND INSTRUMENTATION

An EDAC Quantifier blood circuit monitor (Luna Innovations Incorporated, Hampton, VA 23666, USA: www.lunainnovations.com/) was used to measure the GME in the circuit (Figure Two). The EDAC blood circuit monitor uses ultrasound technology to non-invasively count and classify emboli in the extracorporeal circuit. It simultaneously monitors up to three locations, detects individual microemboli at rates up to at least 1,000 per second, and identifies microemboli from 10 microns in diameter to up to 12.7mm (1/2") diameter. The EDAC won the *Frost and Sullivan North American Patient Monitoring Technology of the Year* award in 2006 for its accuracy and reliability.

The use of EDAC technology can be found throughout research literature, and its effectiveness has been proven. Research has shown that the EDAC system is remarkably more sensitive to emboli than other devices meant for GME detection, such as the Hatteland CMD-10 (Hatteland Instrumenteering, Oslo, Norway) (2, 11). Using an EDAC system, Jones et al. (13) was able to conclude that VAVD at -40 mmHg does not statistically reduce the ability of a bypass circuit to remove gaseous microemboli at lower pump rates. Furthermore, Jones et al. determined an effective way to ensure intersystem and intrasystem reliability when using an EDAC. They suggest injecting one milliliter of air into the circuit and taking repeated counts over a 10 minute period.

Figure 2: EDAC Quantifier blood circuit monitor

A one-way ANOVA was used to test for differences between the mean GME counts or percent removal depending on the distribution of the GME counts (2). Statistical significance was set at $p = 0.05$. Plots were made of GME counts vs. venous line pressure for all three methods.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 RESULTS

One-way ANOVA reveals that the difference between the number of GME introduced during VAVD and the numbers introduced during KAVD and siphon drainage is significant when the venous line pressure is equal to and more negative than -60 mmHg. At a venous line pressure of -60 mmHg, VAVD introduced 3.18 times as many GME as KAVD, and 2.71 times as many GME as siphon drainage. At -80 mmHg, VAVD introduced 2.33 times as many GME as KAVD. There was no significant difference in the number of GME introduced when KAVD was compared to siphon drainage.

Figure 3. The Number of GME* Introduced into the Circuit at the Given Line Pressure After One Minute

Venous Line Pressure (mmHg)	Siphon	VAVD	KAVD
0	-176	-133	-170
-20	-189	35	-122
-40	-49	249	-52
-60	201	545	171
-80	**	594	254

* The number of GME reported is the average number introduced from the three trials for the particular method of venous drainage
** No GME count was recorded for a line pressure of -80 mmHg during siphon drainage because such a pressure could not be achieved

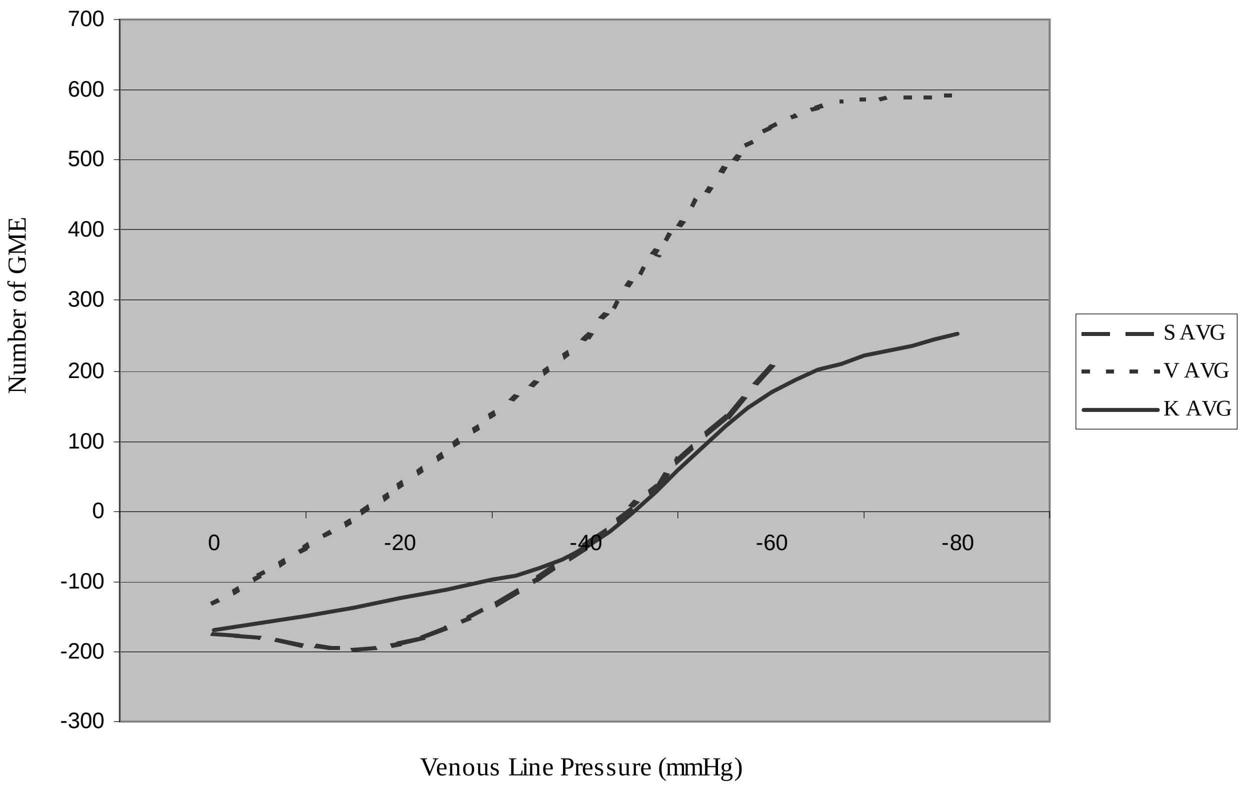
Up to -40 mmHg, negative values were reported for the number of GME introduced. This indicates that emboli entrained in the blood pre-cannula may have gotten caught where the cannula was inserted into the Penrose drain.

Figure 4. Presence and Degree of Vena Cava Collapse (Chugging) at Varying Venous Line Pressures

Venous Line Pressure (mmHg)	Siphon	VAVD	KAVD
0	No	No	No
-20	No	No	No
-40	Yes, weak	Yes, weak	Yes, weak
-60	Yes, strong	Yes, strong	Yes, strong
-80	Yes, strong	Yes, strong	Yes, strong

When the venous line pressures were zero and -20 mmHg, the Penrose drain did not collapse over the tip of the cannula. However, when the pressure was decreased to -40 mmHg, weak collapse was observed for all methods of venous drainage. At -60 mmHg and -80 mmHg, the collapse was strong and occurred regularly at about one chug per second.

Figure 5. The number of GME introduced in one-minute verses the venous line pressure



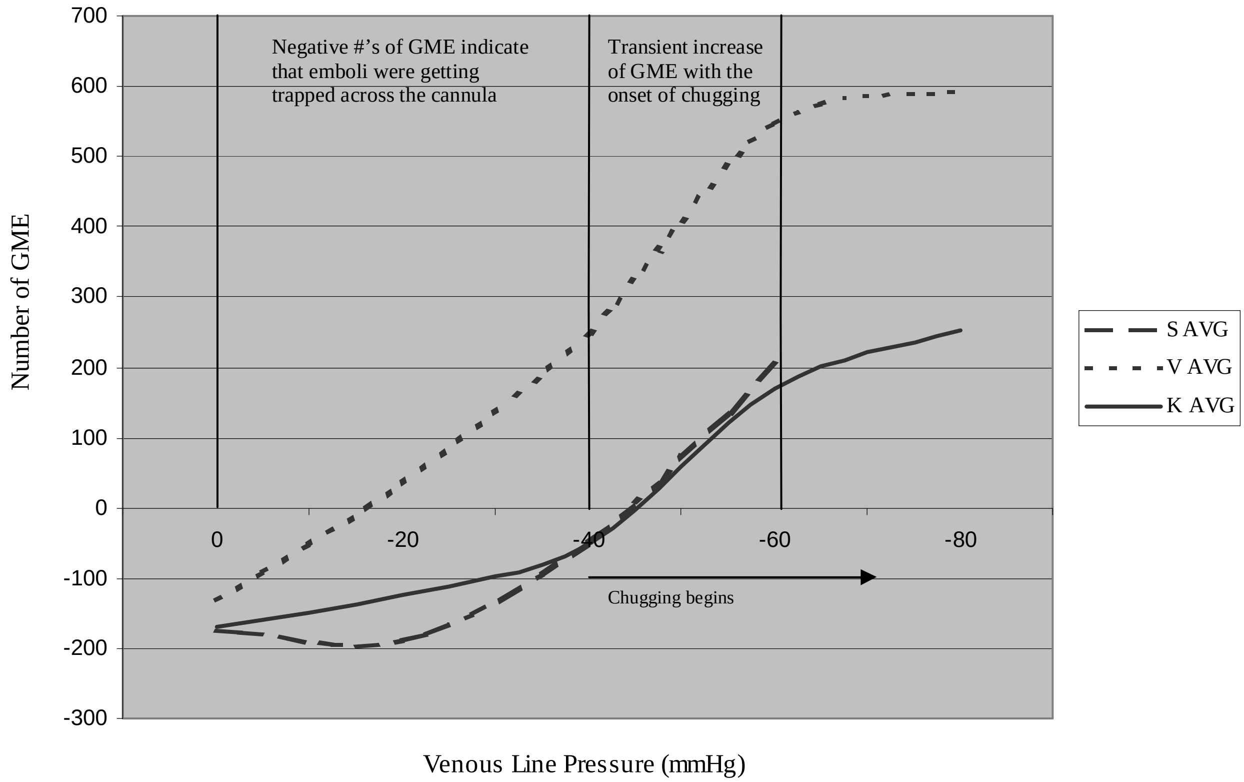
The above graph shows the relationship between the decreasing venous line pressure and the number of GME introduced across the venous cannula. VAVD introduced the greatest number of GME at every pressure, and this difference became statistically significant at -60 mmHg. The point where the graph crosses the x-axis (approx. -45 mmHg for KAVD and siphon, and approx. -15 mmHg for VAVD) represents the pressure at which the GME count leaving the cannula exceeded the count entering the cannula.

3.2 DISCUSSION

At pressures more negative than -60 mmHg vacuum-assisted venous drainage introduced a significantly greater number of gaseous microemboli than both kinetic-assisted drainage and siphon drainage. While the exact cause of such a significant difference is unknown, it is hypothesized that the number of GME introduced correlates with the strength and duration of vena caval collapse over the tip of the venous cannula. The vacuum produced what appeared to be the most powerful chugs; the Penrose drain remained collapsed over the tip for the longest period of time, resulting in excessive negative pressure in the venous line and around the cannula. This can be attributed to the fact that the vacuum provides a constant force of suction. Kinetic drainage on the other hand uses a centrifugal pump, which is preload dependent. The augmentation of the negative pressure across the cannula and in the venous line can only get so great before the pump can no longer sustain forward flow, relieving the venous line of the excessive negative pressure and terminating the chug (15). Similarly, siphon drainage is not able to sustain as negative a line pressure during chugging as vacuum drainage is. Therefore, if vacuum drainage can maintain augmented negative line pressures when the vena cava collapses over the tip of the cannula, there is more time and a greater driving force for air to come out of solution.

With a constant CVP of 5 mmHg, chugging began at a pressure of -40 mmHg. Before -40 mmHg most of the values for the number of GME introduced across the cannula were negative. That would indicate that of all emboli entering the Penrose drain, many would get caught at the tip of the cannula, probably in the space where the cannula was inserted into the drain. Once chugging began however there was a sharp increase in the post-cannula emboli count during all 3 methods of venous drainage. The sudden positive emboli count is most likely the result of two factors: 1) the manipulation of the cannulation site because of the repetitive collapse of the Penrose drain over the tip of the cannula dislodged any emboli that were trapped, 2) the line pressure became more negative as the Penrose drain collapsed over the cannula tip resulting in air being pulled out of solution. The slope of the graph of emboli count versus line pressure increases sharply at around -40 mmHg before leveling off after -60 mmHg, suggesting that there is a transient increase in emboli count as they are dislodged from around the cannula when chugging begins. All three methods of venous drainage demonstrated this trend. The increase in GME count rate is only transient because there are only a finite number of emboli trapped across the cannula. It appears that after about one minute of chugging (right around the time the line pressure was decreased from -40 mmHg to -60 mmHg), most of the trapped emboli were dislodged. The slope of the graph is still positive after -60 mmHg because the increasing negative pressure increases the number of emboli pulled out of solution across the cannula.

Figure 6. Analysis of the graph of the number of GME introduced in one-minute verses the venous line pressure



The above graph shows the transient increase in emboli count after chugging began at -40 mmHg. The rate of GME introduction begins to plateau because there are a finite amount of emboli trapped at the cannula. Despite the decrease in slope, it does remain positive because air continues to be pulled out of solution at more negative pressures

Some limitations did exist in this study. The main limitation was that in order to maintain a realistic on-bypass CVP (0 – 5 mmHg), the flow in the constructed circuit could not exceed 2.5 L/min. For a person with a 2.0 m² body surface area, this would be a cardiac index of only 1.25 L/min/m². Protocols in most institutions state that flows should not drop below a 1.5 L/min/m² cardiac index. If the flow maintained in this experiment was slightly higher, it may have had an effect on the results. For example, the higher flows may have decreased the number of GME that got caught across the cannula, and the transient increases in GME counts that were seen with the onset of vena cava collapse over the cannula tip may not have been as large.

3.3 CONCLUSIONS

The data collected in this lab shows that vacuum-assisted venous drainage introduces a significantly greater number of gaseous microemboli at venous line pressures equal to, and more negative than, -60 mmHg, compared to kinetic-assisted venous drainage and siphon drainage when chugging occurs. Furthermore, it was found that when chugging occurs air is introduced across the cannula in two ways:

1) The augmented negative pressure in the cannula and venous line pulls air out of solution,

2) Chugging manipulates the cannula, dislodging gaseous microemboli that had become trapped where the cannula is inserted into the vena cava.

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